THE DESIGN OF A DIRECT READING SLIP METER

BY

G. J. ZAHROBSKY
L. S. BLOOM

ARMOUR INSTITUTE OF TECHNOLOGY

1921

THE DESIGN OF A DIRECT READING SLIP METER

21203
24

A THESIS

PRESENTED BY

GEORGE J. ZAHROBSKY AND LOUIS S. BLOOM

TO THE

PRESIDENT AND FACULTY

OF

ARMOUR INSTITUTE OF TECHNOLOGY

FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
ELECTRICAL ENGINEERING

JUNE 2, 1921

APPROVED

E. H. Freeman
Professor of Electrical Engineering

Dean of Engineering Studies

Dean of Cultural Studies

THE DESIGN OF A DIRECT READING SLIPMETER

It is only recently that the direct reading slip meter has entered our market. Heretofore, in~~accurate~~ unreliable and peculiar means have been employed in obtaining the slip of an induction motor and the practice of most of these methods has been continued for the very reason that they display uncommon phenomena. The principles, upon which they are based will also be discussed here.

When slip is spoken of, the number of revolutions per minute which the rotor of an induction motor lacks of being equal to that of the revolving field (synchronous speed of motor) is meant, and the percent slip obviously is equal to the ratio of this slip to the synchronous speed. It may be determined roughly by obtaining the difference between the measured speed of the machine (using a tachometer) and the synchronous speed as calculated from the frequency and the number of poles. This is expressed mathematically as follows:

$$\text{Syn. speed} = \frac{\text{Freq. in cycles per sec.} \times 60}{\text{No. of pairs of poles}} \quad \text{or}$$

$$\text{Syn. speed} = \frac{120 \times \text{Freq.}}{\text{No. of poles}}$$

This method, however, is very unreliable as it involves a small difference between two large quantities. For this reason it is preferable to measure slip directly.

The most common method is the use of stroboscopic slipmeters. The name "Stroboscopic" is given to these because of the peculiar effect a flickering light produces on a white disc having black sectors equally spaced. At a recent demonstration and instructive lesson on lighting given at the Central Electric Company of Chicago, it was shown that with a higher intensity of light a black letter on a white card falling rapidly through an aperture could be recognized, whereas, with a slightly lower intensity hardly any conception as to what was on the card could be formed. So in the stroboscopic method used at the Armour Institute of Technology (Fig. 1), the lamp is connected across one phase of the three phase systems, thus giving light fluctuations at a rate equal to the frequency of the source of supply. The disc which is fastened to the induction motor has as many black sectors as there are poles on the motor. In this way if the motor is run at synchronous speed, the disc would appear to remain stationary;

each time the rotor turns through 180 electrical degrees (one pole pitch) there is one alternation of the current wave and each black sector has just enough time during one alternation to occupy the position of the preceding sector. Although the current actually goes through zero value, the rapidity of the change is such that the illumination is decreased very slightly as the white hot carbon still glows. With the induction motor, however, the slip which is inherent, causes the disc to lose its relative position with respect to the light wave and the disc seems to move slowly backward.

A type of stroboscopic slipmeter, which eliminates the arc lamp, consists of two discs; one having black and white sectors symmetrically placed; the other, long slits. The former is fastened to the induction motor and the latter to a small synchronous motor, the shaft of which is in line with that of the induction motor. (Fig. 3) In this manner one can readily see the induction motor slipping and actually count the number of sectors which these

openings pass. If the slip be so great that it is practically impossible to count them, there is a possibility of overcoming this handicap by having but two black sectors. In this case the result will be the slip divided by the number of pairs of poles. In other words, if we multiply the result obtained in this fashion by the number of pairs of poles, we have the slip.

Another type of slipmeter which does not require an arc lamp was suggested by Professor Perkins of the University of Tennessee. (Fig 5) It consists of a disc having a long slender slot, and alternating current electromagnet, and a steel armature suspended by a spring. The electromagnet is connected across one phase of the synchronous vibrations. Hence, its name, the vibrating reed slipmeter. The reed is viewed through the slot. Here again if the rotor were revolving synchronously, the reed would appear to be at the same point with respect to the slot, because the observer always sees it at the same part of its cycle. Since the slip prevents this, the observer always sees it at a slight-

ly different part of its cycle and the result is that the reed seems to move slowly up and down. This motion is proportional to the slip as in the case of other stroboscopic types of meters and the number of oscillations per minute gives the slip.

The time that is required in fastening and removing the disc to and from motors in the stroboscopic method forbids the use of the latter in places where motors are tested regularly. More suitable devices have been devised to meet this condition.

One device of this kind is the commutator type slip meter, which was invented by Cooley. (Fig. 4) A cylinder, which is composed of two insulated parts, acts as a sort of commutator, which has as many segments as the motor has poles. The position of the brushes 1 and 2, is such that as the commutator revolves, its two parts are constantly being short circuited through an ammeter (or D.C. polarized ball). The other two brushes, 3 and 4, are connected through a resistance, r, across one phase of the system. The current reverses in the ammeter for each successive short circuit. If the meter were pressed

against the end of a synchronous motor shaft , the ammeter would give a constant current reading equal to the voltage across one phase divided by the resistance, r. At a speed below or above synchronism the ammeter indicates an oscillating current because the impulses of current through the brushes, 1 and 2, occur at the same point on the wave. In this way the ammeter reading is reversed once each time the motor loses half a cycle and reads its maximum positive value for every loss of one cycle. If, therefore, the motor loses n cycles per minute, the slip in percent may be expressed algebraically:

$$\text{o/o slip} = \frac{100n}{60f}$$

where f is the frequency of the system in cycles per second.

Another form of commutator slip meter which reads both actual speed and slip is the Bianchi automatic slipmeter, (Fig 6.). While in its principles it is similar to the Dooley motor, it has an attachment for automatically registering the number of revolutions of slip. This is accomplished by sending the impulses obtained from one phase of the system through the

electromagnet, E. M., which gives a pulsating motion to the permanent magnet, P. This, in turn, actuates a rachet - and - pawl recording mechanism. Thus the slip is recorded on the dial #1. The part (2) beyond the commutator is a tachometer which gives the actual speed of the motor. The sum of the two readings, 1 and 2, gives the synchronous speed, and consequently, the frequency of the supply.

For low line voltages the electromagnet is thrown across one phase through a resistance, (R, or (R R), as shown in accompanying figure. For high voltages the instrument is connected across one phase through a potential transformer, (P. T.). The "commutator" is composed of one collecting ring and a number of slender commutators, which are insulated from each other. Each of the commutators has a different number of segments so as to enable the manipulator to read slip directly for motors having any number of poles. The brush, B. is fixed to the collecting ring, while the brush B is capable of being moved to any one of the commutators. An index plate shows the position of the movable brush for any number of poles.

There is also a method of obtaining slip from the circle diagram of an induction motor. The diagram is drawn from data giving relations of current, voltage, and power input at various loads including no load, and locked rotor. From this diagram, moreover, the complete performance of the motor may be ascertained. Since slip varies at the load for a certain range, all other values depend on it. This can best be made clear by describing a commercial test.

The machine is allowed to run without load having rated voltage applied to the terminals. The ammeter reading, the no load losses, which consist of the core losses, windage, and friction. These combined losses of windage and friction are so small that the wattmeter indication may be considered to be due solely to the conductance of the circuit. The magnetizing current, MO, may be considered as having components in time phase and time quadrature with the voltage (Fig. 6). The magnituted of these components is procured by drawing the magnetizing current to scale at the correct power factor angle, θ, where θ

is the calculated value from the formula,

$$\text{Cos. } \theta = \frac{\text{Wattmeter reading}}{\text{Voltage x Current}}$$

The projection of this current vector upon the voltage vector then gives the in phase current, M. N, which is equal to the core loss, windage, and friction.

The rotor is now locked and sufficient voltage is applied to give about twice the full load current in the primary. Since the current is practically proportional to the voltage at standstill, the value of the equivalent primary current at the rated voltage is calculated by simple proportion $(\frac{E_1}{I_1} = \frac{E_2}{I_2})$. The value of this vector, MQ, is drawn in a similar fashion at its correct power factor angle. The extremities of these vectors are connected giving the resultant equivalent secondary current at standstill, OQ. The line OV is drawn to show the no load losses, which are constant. This line is on a diameter of the circle diagram. Having the diameter and two points of a circle, O and Q, it is an easy matter to drawn the circle. The line, QS, is cut at G so that QG and GS are in the same ration as the second ry and primary copper losses. It will be noted, however, that the copper loss (wattmeter reading) is

proportional to the square of the current.

The circle thus drawn gives the locus of the secondary current. For any point, P, the following values are given directly from the diagram;

PM = Primary Current.
PO = Secondary current.
MO = Magnetizing current.
PL = Input in watts.
HK = Primary copper loss.
FH = Secondary copper loss.
FP = Mechanical load, output in watts.

$$\text{Power factor} = \text{Cos (EMP)} = \frac{PL}{PM}$$

$$\text{Efficiency} = \frac{FH}{PL}$$

$$\text{Slip} = \frac{\text{rotor loss}}{\text{rotor input}} = \frac{FH}{PH}$$

The working part of this curve is so small that it is practically impossible to obtain results which are sufficiently accurate to justify its use in obtaining slip.

A type of meter which approaches nearest to the meter to be designed is one, which has a conical drum and a disc, carrying a stroboscopic disc. The latter discs are on one shaft held in a rider so that the driving disc may be placed at will at any part of the drum (Fig 5) The drum is driven by the induction motor under test. By

setting the disc at a point where it will run in synchronism with the source of supply (or the light), the slip may be read directly on a scale as shown. This method has the disadvantages of being non automatic and using an arc lamp. Its accuracy, however, is excellent (about [illegible]).

A slip meter which excels all these by far is that suggested by F.E.Myard in an artical of the Revue Generale d'Electricite' (Jan. 19, 1920). This is the one which has been designed and constructed by the authors. Its principle, design, and construction will now be discussed.

The theory upon which it is based is very simple, but the mechanical details which are involved in its design are rather difficult. Primarily it consists of two discs. The larger of these is connected through gears and a flexible shaft to the induction motor. The smaller disc is free to move on a threaded shaft of a synchronous motor. (Fig. 10). As the flexible shaft is connected to the induction motor, it revolves the larger disc, which in return drives the smaller. In so doing the latter screws up as it were to a collar, which does not permit it to move along the

shaft. Now the small synchronous motor is driven to such a speed that it is able to "pick up", For a synchronous motor is not self starting. As the synchronous motor picks up its shaft screws the smaller disc forward or backward to a point of equilibrium, i.e. since the peripheral velocity of the points of contact of the two discs must be the same (without skidding) and since the radius of the smaller disc, r, is fixed then the distance R of the point of contact of the discs from the center of the larger disc is given by the formula:

$$2\pi rN(act.) = 2\pi RN(syn.),$$

from which $R = \left(\frac{N(syn.)}{N(act.)}\right) r.$

This shows that the slip is proportional to the distance, through which the small disc moves.

In order to utilize the motion of this disc as a means of reading the slip directly, a small slot is machined into its hub and an actuator suspended from the frame of the meter is placed into this slot. A string, tied to the actuator and wound over a minute drum, transfers the motion to the dial, which is held in place by

by the counter - torque of a small spring.

The bill of material is as follows:

(1) Frame - machined from 8" pipe length.

(2) Front panel - cast iron- machined for glass front.

(3) Back panel - cast iron- with bearing for shaft of large disc.

(4) Two gears - brass- ration 2:1.

(5) Special bracket - sheet iron and soft steel connecting gear to flexible shaft.

(6) Clutch - soft steel.

(7) Flexible shaft - without links.

(8) Large disc - aluminium.

(9) Spring - compression - to hold discs together.

(10) Small disc- fiber riveted to steel hub (tapped).

(11) Actuator - soft iron.

(12) Dial support - soft iron.

(13) Pointer shaft with small drum.

(14) Synchronous motor
- (a) rotor - with long shaft threaded on one end.
- (b) Stator - laminated iron.
- (c) Winding - #27 wire.
- (d) Front and back panels - cast iron.
- (e) Insulators.
- (f) Special bracket for motor - cast iron.

(15) Inductance coil - laminated iron #27 wire - two taps n = 250, n = 500.

THE SPLIT PHASE SYNCHRONOUS MOTOR

It is unnecessary to point out here in detail why a single phase induction or synchronous motor has no starting torque. The reason for this is that only polyphase motors have rotating fields, while the single phase machines have only a pulsating field. If, however, the rotor in either type of motor is started in some other way, the inertia will carry it from one pole to the other as the polarity of the field reverses. Only a little twist on the rotor of a single phase induction motor is required to start it, while the synchronous motor must be brought up to practically synchronous speed before it will continue to run.

Where there is single phase power and a motor with a rotating field is desired, it is possible to use a split phase affair. Such a motor is essentially a two-phase machine. The current in one phase is made to differ in time from the current in the other by reducing

the voltage in one phase through a resistance and in the other through an inductive or capacity reactance. Of course, such a motor is inefficient due to the fact that there is a large resistance loss in one phase and there is large quadrature current in the other phase, which makes a low power factor. The voltage impressed upon the motor must necessarily be small. Hence this scheme can be used only on small induction motors. The ideal condition would be if one phase contained pure inductance and no resistance, while the other phase contained pure resistance and no inductance. Then the currents would differ in phase by 90 degrees. Since such a condition is impossible of attainment, the currents will differ by less then 90 degrees. This condition is illustrated in Fig. 8. I_1 is made up mostly of phase current and partly of quadrature current while I_2 is made up in the reverse order. The angle θ is less then 90° . it is actually possible to get a 90° phase relation by having an inductance in one branch and a condenser in the other. The vector diagram (Fig. 9) illustrates that the current I_4, consists of some inductive, and mostly condensive

and resistance current, while I_2 is composed of resistance and inductive current. This arrangement however, is impractical, for the capacity required for low frequencies is excessive and the cost of a condenser of this capacity would make it prohibitive. The discussion has been of an induction motor, but it is easy to see that the principle can be applied to a synchronous motor.

In designing the little synchronous motor for the slipmeter much of the work was experimental, as no such motors are on the marked, and no data can be obtained for its design. We made the stator of laminated iron, which has eight polar projections on it. The winding per pole for each phase was made to cover two projections, thus giving four poles per phase. Both windings were displaced by one projection. In other words there was a space difference of 90 electrical degrees. The rotor was made of ordinary machine steel, in which four slots were milled out to produce polar projections. These were not

magnetized; we made an attempt to have the motor start by its own power, and in so doing put on the rotor an amortisseur winding, which would give the rotor a starting torque and bring it up to almost synchronous speed. The rotor, not being permanently magnetized, would then have induced in it a current, which would set up a field to react with the rotating field to produce the torque, very little of which is necessary.

As stated above, no perliminary calculations could be made, and the stator and rotor had to be made according to general proportions and the windings would on, number 27 wire was used on the stator. This has a current carrying capacity of about 0.5 or 0.6 ampers. There are 25 turns per pole and hence 100 turns in all per phase. The dimensions of the important parts as follows:

Width of rotor pole face	=	0.75"
Length of rotor	=	1.5"
Length of air gap	=	$\frac{1''}{32}$

From this the inductance, L, is calculated

$$L = \frac{3.2 \ n^2 A}{10^8 x l}$$

$$L = \frac{3.2 \times 10^4 \times .75 \times 1.5}{10^8 \times \frac{1}{16}} = 0.00575 \text{ henries.}$$

Considering 25 cycle current and 80 volts , which is the rating of several of the induction motors in the Institute, we obtain the synchronous reactance of the motor per phase, X.

$$X = 2\pi fL$$

$$X = 2\pi \times 25 \times 00.00575 = 0.9 \text{ ohm}$$

The resistance per phase is 2.5 ohms.

Assuming 0.5 ampers, the drop across the motor is

$$0.5 \times \sqrt{0.9^2 + 2.5} = 2.65 \text{ volts.}$$

In the resistance circuit the current will be almost entirely in phase, hence the resistance to be added should be in the neighborhood of 157 ohms. In the inductive circuit we can neglect the resistance of the motor winding, and assume that we need an impedance of 160 ohms. As the resistance of the inductance coil is not known, we may assume about 140 ohms reactance. This value may be easily varied after the winding is on by changing the length of the air gap.

The core of the inductance coil is made up of laminations. The cross section of the smallest flux carrying portion is $^{11}/_{16}$" by 1-$^5/_8$", and the mean length of the core is 13" . Assuming an air gap of about 0.01 inch, we have

$$L = \frac{3.2\ n^2\ A}{10^8 . l}$$

where l is the length of the air gap in inches, since the reluctance of the iron is about $\frac{1}{3000}$ that of air and may there fore be neglected. Thus

$$2\pi fL = 140$$

$$L = \frac{140}{2\pi} \times 25 = \quad \text{henry}$$

Now this is equal to the above or

$$0.9 = \frac{3.2\ n^2 \quad (11/16 \times 13/8)}{10^8 \times 0.01}$$

from which n = 500 turns.

If the resistance of the inductance coil is large, so that the total impedance is greater than 160 ohms either the numb r of turns should be reduced or the length of the air gap increased a trifle. As was pointed out before, the resistance should be as small as possible in order ot obtain a great r phase difference.

It is evident that at 60 cycles the inductance should be smaller. The number of turns required is calculated in the sam fasion as shown above and a tap is brought out from the correct turn.

It may seem as though we were traveling from the subject in discussing these calculations. It should, however, be remembered that there are no published data on such small synchronous motors, which cannot be designed as the larger machines, in which the fields are either permanently magnetized or excited by a direct current. Those machines can be designed roughly as alternators taking into consideration the field flux, current carrying capacity, phase relation, armature reaction, etc. This has practically no counter e.m.f. and must be considered to be a simple inductance coil, having inductance and resistance. The little synchronous motor was really the big problem in the construction of the slipmeter.

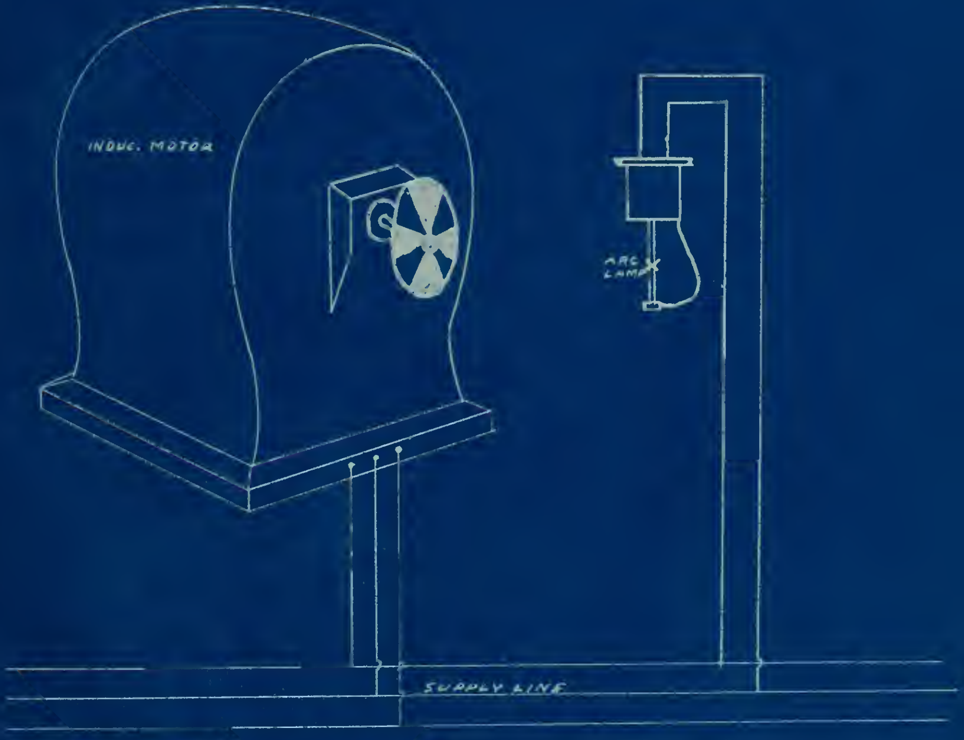


FIG 1.

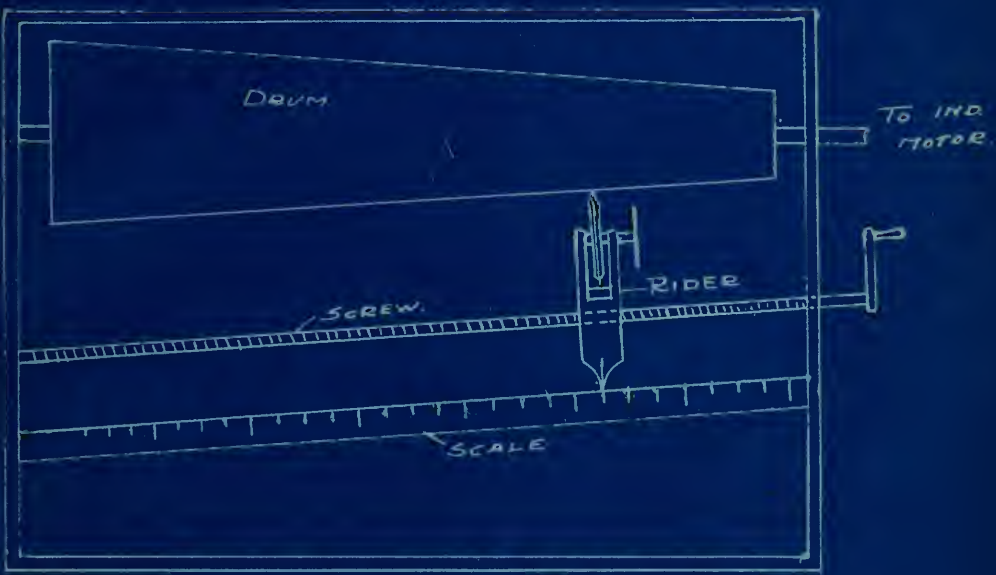


FIG. 2

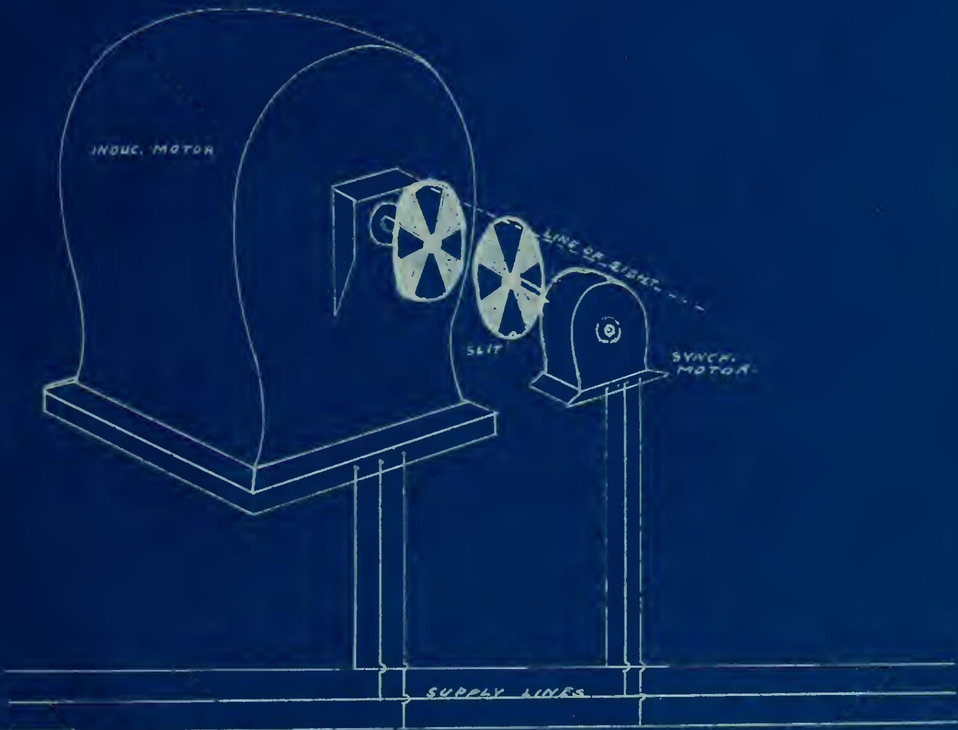


FIG. 3

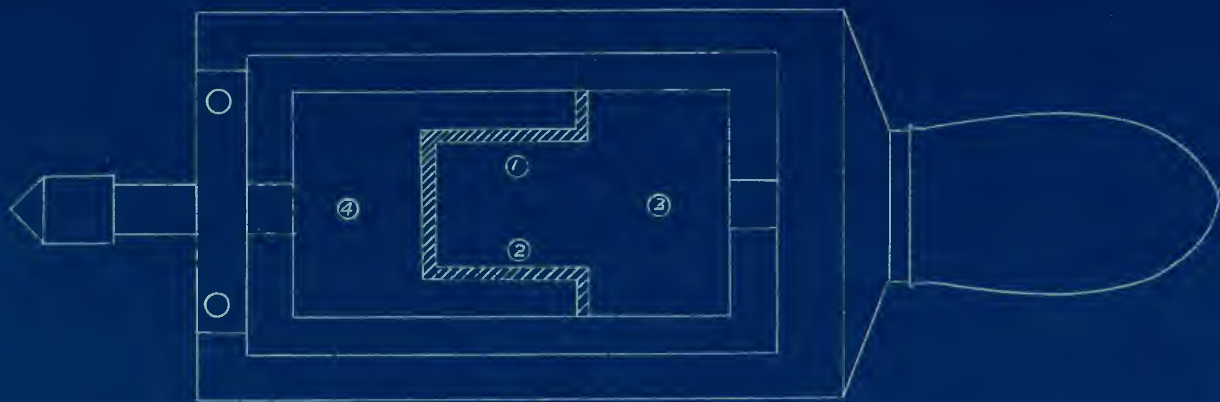


FIG. 4

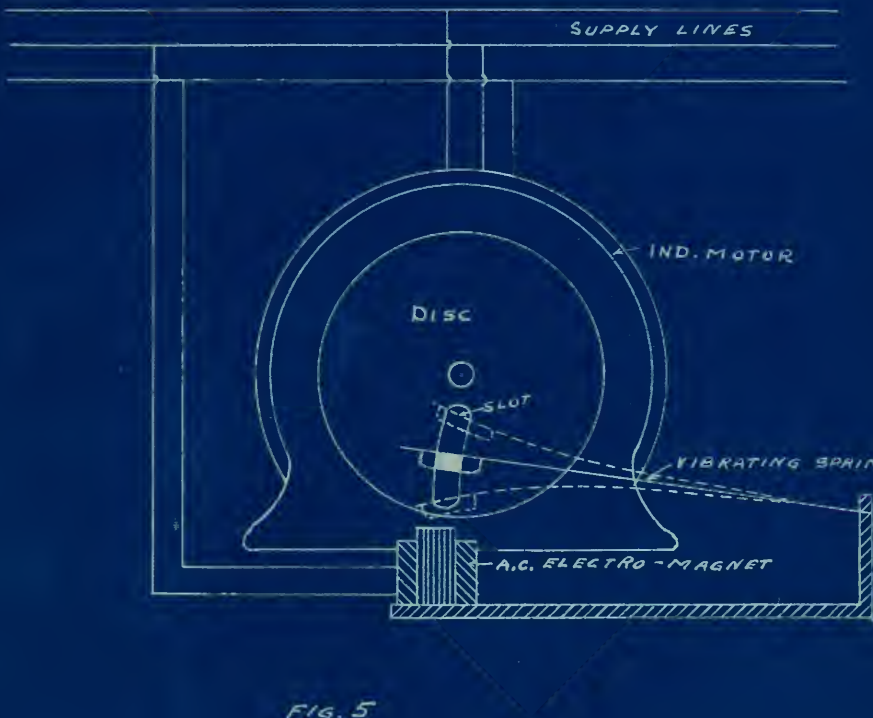

SUPPLY LINES
IND. MOTOR
DISC
SLOT
VIBRATING SPRING
A.C. ELECTRO-MAGNET

FIG. 5

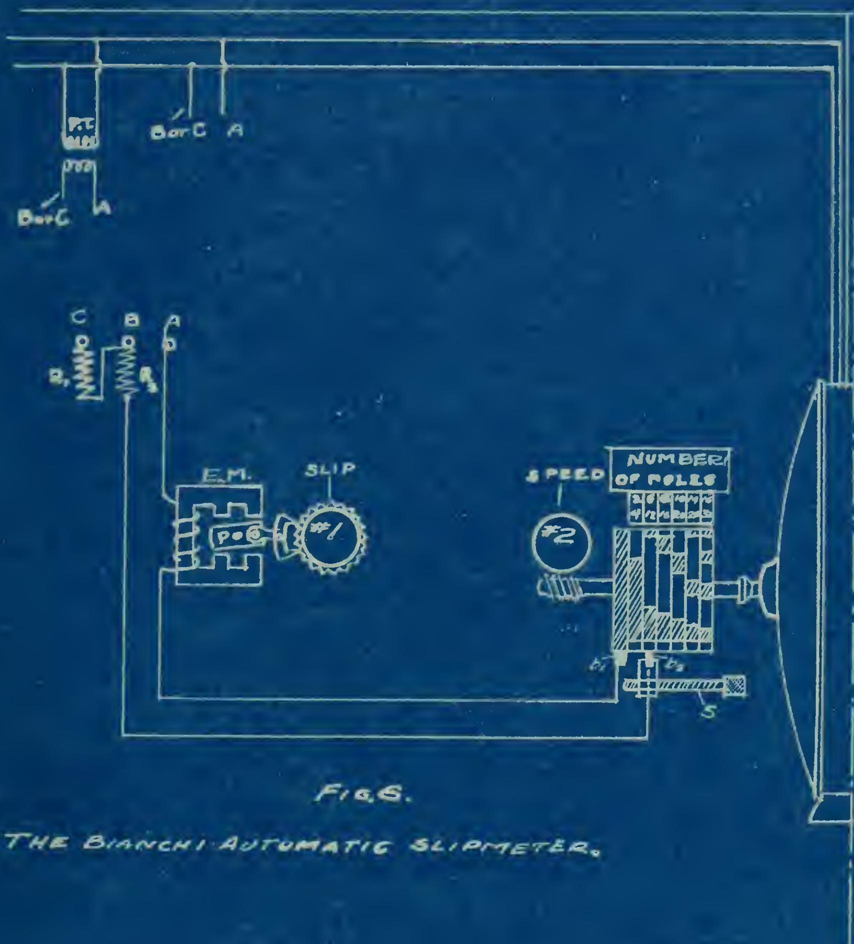
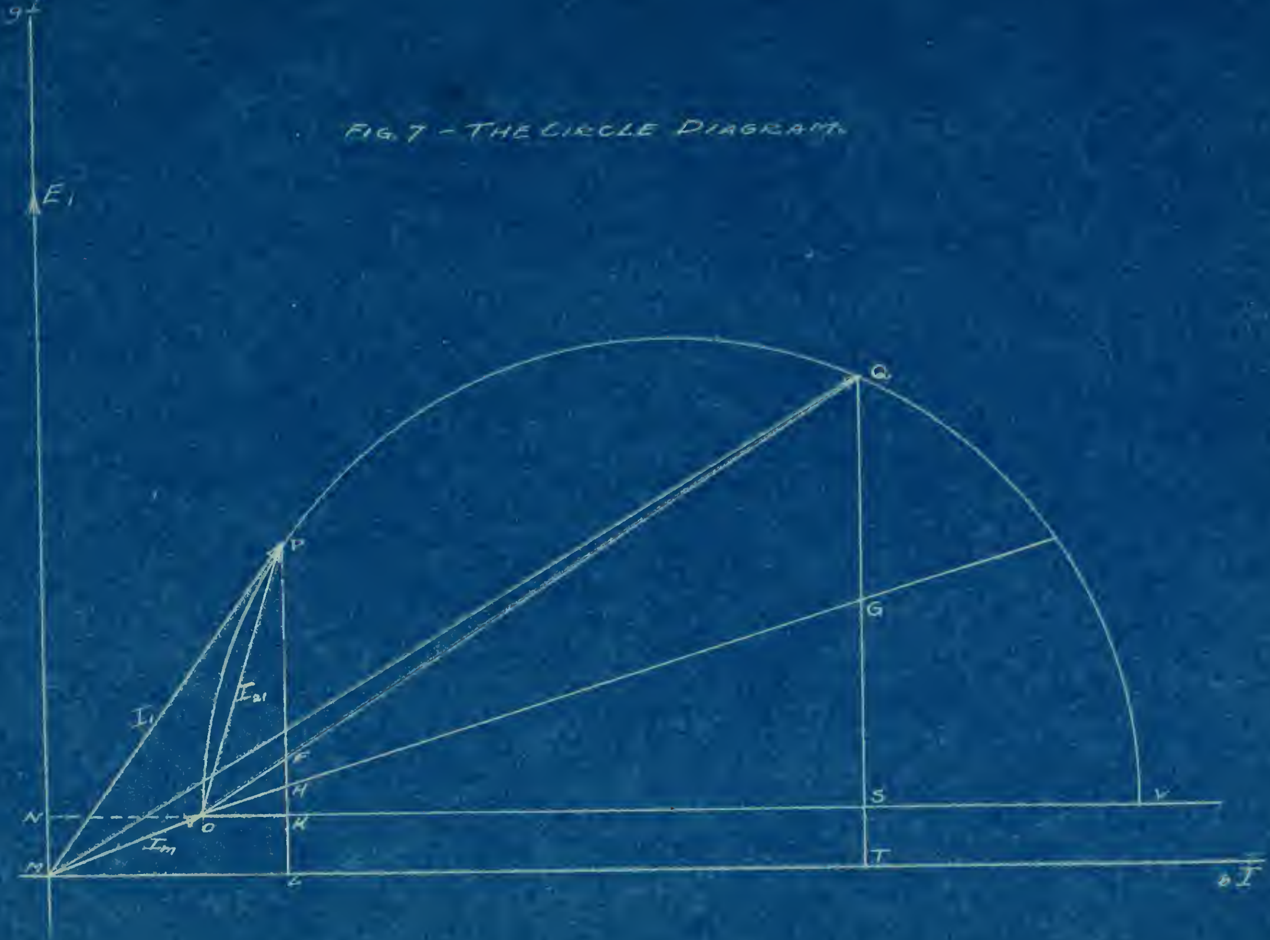


FIG. 6.

THE BIANCHI AUTOMATIC SLIPMETER.

FIG. 7 - THE CIRCLE DIAGRAM.



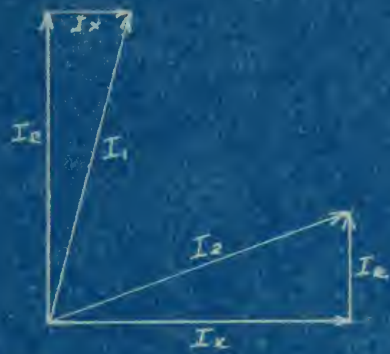


FIG 8

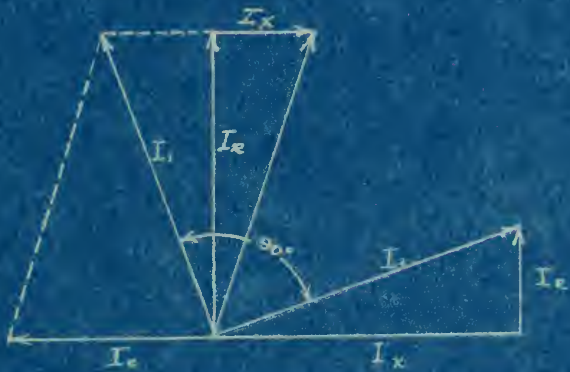


FIG 9


SYN.
MOTOR
CORD
ACTUATOR
DRUM
DISK
SPRING
FRAME
FLEXIBLE
SHAFT
GEARS

FIG 10